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AD-A224 327

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE 25 May 1990

3. REPORT TYPE AND DATES COVERED Annual Technical 15 May 89 - 14 May 90

4. TITLE AND SUBTITLE

Particle Dispersion in a Turbulent Shear Flow

5. FUNDING NUMBERS

PE - 61102F
PR - 2308
TA - A2
G - AFOSR 89-0392

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8. PERFORMING ORGANIZATION REPORT NUMBER

AFOSR-TR- 90 0685

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFOSR/NA
Building 410
Bolling AFB DC 20332-6448

DTIC ELECTE 1990 S D

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

A joint experimental and numerical study of droplet dispersion in a round turbulent jet has been initiated. Laser light scattering was used to measure the motion of non-vaporizing droplets of water and hexadecane in an isothermal turbulent jet of air. The results indicated that an initial radial velocity fluctuation in the droplet motion at the jet exit can serve to increase significantly the dispersion of droplets larger than 100 µm. Vortex dynamics simulations of the near region of the jet showed that Basset, virtual mass and pressure gradient forces may be neglected for small droplets but may need to be accounted for, particularly at high pressure, with large droplets (> 100 µm) even if the drop to gas density ratio is close to one. A stochastic simulation of particle dispersion revealed that the Reynolds stresses or velocity correlations in this flow do not contribute significantly to particle dispersion.

14. SUBJECT TERMS

Turbulent shear flows, particle dispersion, vortex dynamics, stochastic simulation

15. NUMBER OF PAGES 7

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

90 06 26 047

Standard Form 298 (890104 Draft) Prescribed by ANSI Std. 239-18 298-01

RESEARCH OBJECTIVES

AEOSR-TR- 90 0685

The overall objective of the project is to test current modelling of droplet scale processes for spray combustion in a well defined, turbulent shear flow by comparison of measurements of droplet dispersion and vaporization rates with numerical predictions. Our specific goals in this year of the project were firstly to develop the experimental apparatus and to obtain initial measurements of droplet dispersion for a cold flow with non-vaporizing droplets. A range of droplets between 50 μm and 150 μm diameter were to be achieved so as to give a range in the droplet response time compared to turbulence time scales. The laser diagnostics that were needed to detect particle position in the flow were also to be developed in this year.

The numerical phase of the project aimed to develop a vortex dynamics simulation of the turbulent jet. Particles were then to be injected numerically and their motion was to be followed by integrating the droplet equation of motion. One factor that was of interest was the impact of the Basset, virtual mass and pressure gradient terms in this equation on the dispersion of particles.

RESEARCH ACCOMPLISHMENTS

Experimental: An experimental apparatus has been constructed. It consists of a chamber which houses a piezo droplet generator. A round nozzle of 7 mm diameter is attached to the chamber. Droplets are generated by the piezo device and are injected onto the centerline of the jet. Electronics have been developed which permit us to control the rate of formation of droplets and the synchronization of the detector electronics with the droplet generator. At present we are using air as the jet fluid.

The jet turbulence has been characterized with a hot wire anemometer set. This gave profiles of mean velocities and turbulence intensities. FFT analysis of the velocity records yielded frequency spectra of the flow field which allowed length scales to be estimated. The spectra indicated that the jet turbulence was fully developed with about three decades of frequencies. The spectral decay approximated the classical -5/3 behavior.

Considerable effort went into the design and the manufacture of the nozzle. An ideal nozzle would produce a top-hat velocity profile at its exit but would not accelerate the flow excessively such

that the droplets become distorted due to large relative velocities. This latter factor is particularly important for larger particles. Two nozzle were tested in order to achieve a satisfactory performance. All droplets appear at the nozzle exit as spheres.

Initially we were generating droplets of the order of 150 μm diameter. Some time was devoted to modifying the piezo droplet generator with a pinhole orifice to generate much smaller particles. Currently we are able to produce 65 μm droplets; this is the approximately the smallest size at which the detection optics yield reasonable signal to noise ratios.

Two detection systems have been evaluated The first technique made use of a two dimensional lateral effect photodiode. Imaging the droplet scattering onto the photodiode produced four photocurrent outputs which yield the X-Y position of the droplet image when they are suitably subtracted and divided. Considerable work went into designing, building and perfecting the electronics which we use to convert the current to voltage, filter the signal with a low pass filter and then detect the signal peak. A limitation of the 2D detector is its relatively large active area which tends to produce quite significant dark noise; this noise limits the ultimate resolution in particle position which we are able to achieve. Consequently, we have recently evaluated a one dimensional position sensing diode. The dispersion can be obtained from this 1D measurement by assuming statistical independence of the X and Y locations of the droplets. Because of its smaller active area it is less noisy but we have discovered that it suffers from a problem that is associated with the depth of field of the collection optics and the attendant defocussing of the particle image for locations close to or far from the collection lens. Because the diode detects the centroid of an image whether it is in focus or not, an ambiguity is introduced into the measurement wherein droplets at different radial locations on either side of the focal plane may yield similar measured positions. We are currently installing a 2D position sensing photomultiplier which we believe can give a much improved resolution of droplet motion. It has sufficient frequency response that we may be able to track the droplet position as it traverses our laser sheet, thereby obtaining quantities such as the Lagrangian autocorrelation function. The extra resolution and low noise of the PM tube will be particularly advantageous when we have to deal with vaporizing droplets which may quickly reduce to quite small sizes.

Measurements have been obtained in a turbulent jet with a Reynolds number of 15,000. Water and hexadecane have been used to make droplets that range in size from 65 μm to 150 μm diameter.

Droplet dispersion (mean square displacement from the centerline) has been measured as both a function of axial position in the jet and as a function of the droplet time of flight. The latter quantity was obtained by measuring the droplet velocities.

One very important finding is the apparent importance of the droplet initial conditions on dispersion for the larger particles. Our initial measurements of particles greater than 100μm produced dispersions which were much greater than we predicted with a stochastic simulation. However, the slope of the dispersion curve versus time of flight squared yields an estimate of the initial rms velocity fluctuations of the particles as they enter the jet. When these values were used in the simulation very good agreement was obtained between the experimental and the numerical dispersion results. The numerical simulations indicate this effect may extend down to particles as small as 80 μm. This result bears important ramifications for spray modelling in that a significant fraction of a spray may be controlled more by the initial conditions of velocity fluctuations than by the turbulence of the flow field itself. Given the difficulty in prescribing the initial conditions in a spray , this result may imply that there is some potential difficulty in determining the dispersion of droplets.

A further experimental finding which is of some interest is the behavior of the dispersion of droplets as a function of the time of flight. The theory of Taylor for fluid particle dispersion in a homogeneous turbulence indicated that the dispersion should increase as time squared for early times and as a linear function of time for later times. There is no fundamental reason to expect similar behavior for discrete particles in a shear flow although Batchelor argued that , given appropriate self-preserving scaling, fluid particles may exhibit this behavior. Our results appear to indicate that the larger particles follow the Taylor theory but whether this results from their sensitivity to the initial velocity fluctuations which they inevitably possess remains to ascertained in experiments that we shall conduct with different particles. We are currently planning to do a series of experiments with hollow glass spheres which have a large light scattering cross-section and yet follow the flow better than the droplets that we have used.

Numerical Results : Two numerical approaches have been explored in this year of the project. The first method is based on vortex dynamics. We developed a three dimensional code for modelling the near field of a turbulent jet at approximately the same conditions as the experiments. Particles were injected numerically

into the calculation and their equations of motion were solved. One question that we wished to answer in this work was the importance of the Basset, virtual mass and other forces that are conventionally ignored in droplet dispersion calculations, simply on the basis of a large ratio of droplet density to gas density.

The implementation of the full droplet dynamics calculation in the vortex dynamics code presented substantial numerical difficulties. The Basset term, in particular, was difficult to handle because it introduced an integral into the differential equation for droplet velocity. These terms also depend implicitly on the velocity. The drag coefficient was calculated as

$$C_d = \frac{24}{Re}\left[1 + 0.15\, Re^{0.67}\right]$$

It was found that the three dimensionality of the flow did not have a great effect on the dispersion of droplets in the azimuthal direction over a range of locations close to the nozzle exit i.e., down to about eight diameters. Therefore we decided to continue the calculations with a much faster 2 D code.

Calculations were performed for a range of droplet diameters and pressures up to 20 atmospheres. The computations were checked against analytical solutions for droplet motion in sinusoidally varying velocity fields with excellent agreement. The major finding was that over the full range of pressures which we studied it is justifiable to ignore the Basset, virtual mass and pressure gradient terms for droplets of density 1000 kg m^{-3} with diameters less than about 50 μm. However, large droplets with diameters on the order of 150 μm exhibited effects of the Basset, virtual mass and pressure gradient forces on the order of 30% of the drag force. This effect was exacerbated at 20 atmospheres so that somewhat smaller droplets exhibited an effect. The results were obtained in a region of high fluid accelerations and the impact of the additional terms on droplet motion in the far field of the jet are expected to be considerably less. However, the results do indicate that a small droplet to gas density ratio is not a sufficient condition to justify the neglect of Basset and other terms in the droplet equation of motion, particularly at high pressure. We also concluded from this research that the vortex dynamics method is not an appropriate way to calculate the full jet flow field due to its assumption about the structure of the vortex filaments; it is most useful in the near field of the jet where vorticity is concentrated into rings.

The other numerical approach which has been used is an adaptation of the stochastic simulation which was first proposed by Gosman and Ioannides and later used by Faeth and co-workers. We have improved on this approach by calculating the flow field with a Reynolds stress model which gives us the correlations between velocity components. This information permits us to evaluate one of the common assumptions in droplet dispersion calcualtions viz., that the shear stresses play no role in particle dispersion. The effect of the turbulent shear stresses has been incorporated into our stochastic simulation by performing a coordinate rotation each time a velocity pdf is sampled. This rotation imposes a correlation on the velocity components. Hence we have been able to evaluate the role of the Reynolds stresses in particle dispersion in shear flows and we find that the effect is small for particles less than $10\mu m$ and is negligible for larger particles. This is the first time that the neglect of the shear stresses has been demonstrated to be reasonable in a turbulent shear flow.

A second important outcome of our stochastic modelling arose from our efforts to predict the dispersion data from our experiments. Initially we had little success in matching the observed dispersion rates. It was not until a random radial velocity was applied to the droplets at the nozzle that good agreement with the experiments was obtained. Subsequent testing of the effect of initial conditions on droplet dispersion indicated that the effect may extend down to droplet sizes which incorporate a significant fraction of the mass in a typical spray.

PUBLICATIONS

C. Call and I. M. Kennedy, Particle Dispersion in a Turbulent Shear Flow, Paper 90-0468, AIAA Aerospace Sciences Meeting, Reno NV, Jan. 1990.

C. Call and I. M. Kennedy, The Dispersion of Non-Vaporizing Droplets in an Axisymmetric Turbulent Jet, submitted to Experiments in Fluids, May 1990.

I. M. Kennedy and W. Kollmann, Simulations of Particle Dispersion in a Turbulent Jet, to be submitted to Int. J. Multiphase Flow, July 1990.

D. Hansell, W. Kollmann and I. M. Kennedy, Vortex Dynamics Calculation of Particle Dispersion in Round, Turbulent Jet, to be submitted to Physics of Fluids, July 1990.

INTERACTIONS

Papers based on this work have been delivered in the following venues:

(1) Western States Section Meeting of the Combustion Institute, Livermore CA, October 1989

(2) 10th Australasian Fluid Mechanics Conference, Melbourne, Dec. 1989.

(3) AIAA Aerospace Sciences Meeting, Reno NV, Jan. 1990

(4) Poster presentation at the 23rd Int. Combustion Symposium, Orleans, France July 1990.

PERSONNEL

I. M. Kennedy   P.I.   15% time
W. Kollmann   P.I.   10% time
C. Call   Ph. D. Candidate 50% time
D. Hansell   M. Sc. Thesis title "A Study of Particle Dispersion in the Transition Region of a Round Jet", May 1990.

INVENTIONS

None